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Abstract

A novel empirical-based Delamination Reduction Trend (DRT) for stitched composites has been recently proposed. The DRT is capable of predicting the effective reduction in impact-induced delamination area due to the influence of stitching. DRT simply relates two parameters: normalised delamination area and stitch fibre volume fraction, to characterize the effectiveness of stitching in impact damage suppression. This paper seeks to validate the DRT by using quasi-static indentation (QSI) test, which is considered analogous to low-velocity impact test, due to similar structural response. Results from QSI test show good agreement with DRT. Furthermore, limitations in DRT have been established.

1 Introduction

Stitching has been proven to be effective in increasing delamination resistance and improving impact damage tolerance of laminated composites [1]. Recently, a novel empirical-based Delamination Reduction Trend (DRT) for stitched composites has been proposed [2]. The DRT is capable of predicting the effective reduction in impact-induced delamination area due to the influence of stitching. DRT is identified and developed based on an extensive series of low-velocity impact (LVI) tests using specimens of different laminate thicknesses, stitch densities and stitch thread thicknesses, subjected over a range of impact energy levels. The DRT simply relates two parameters: normalised delamination area ($Delam_{Norm}$- calculated by dividing the impact-induced delamination area of stitched specimen over the delamination area of unstitched counterpart), and stitch fibre volume fraction (V_{ft} - the percentage of stitch thread fibre in the material) to characterize the effectiveness of stitching in impact damage suppression (Figure 1). DRT evidently shows a bi-linear behaviour: first, an initial linearly decreasing relationship of $Delam_{Norm}$ with V_{ft}; and second, a plateau which indicates maximum delamination area reduction limit of 40% by stitching (Figure 2). Experimentally observed damage mechanisms are presented and discussed in [2] with the aim to justify and explain the bi-linear behaviour of DRT. The DRT has also been validated with numerous published literature results and has demonstrated excellent agreement.

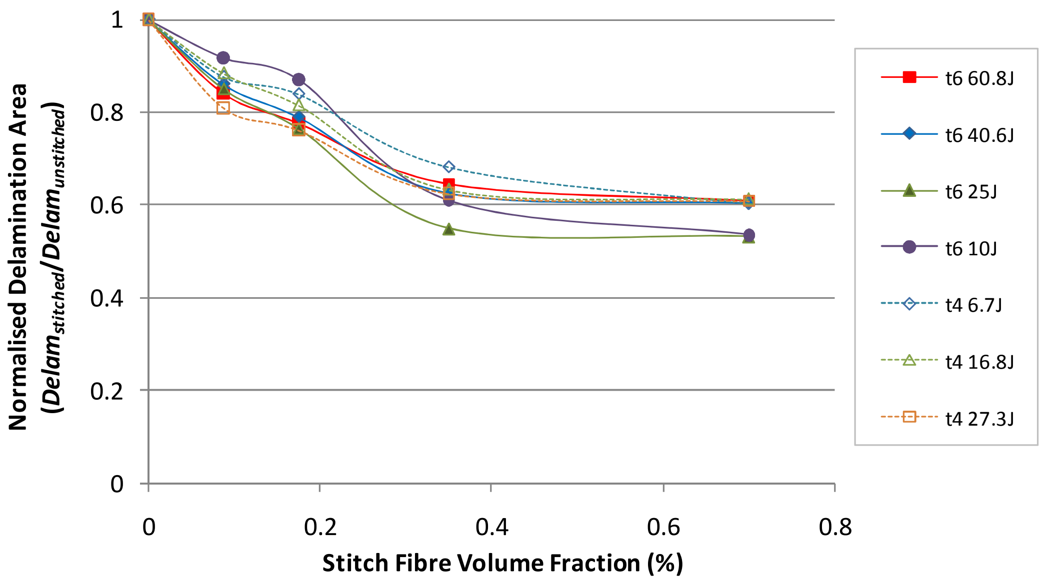

Figure 1. Normalised delamination area against stitch fibre volume fraction [2].

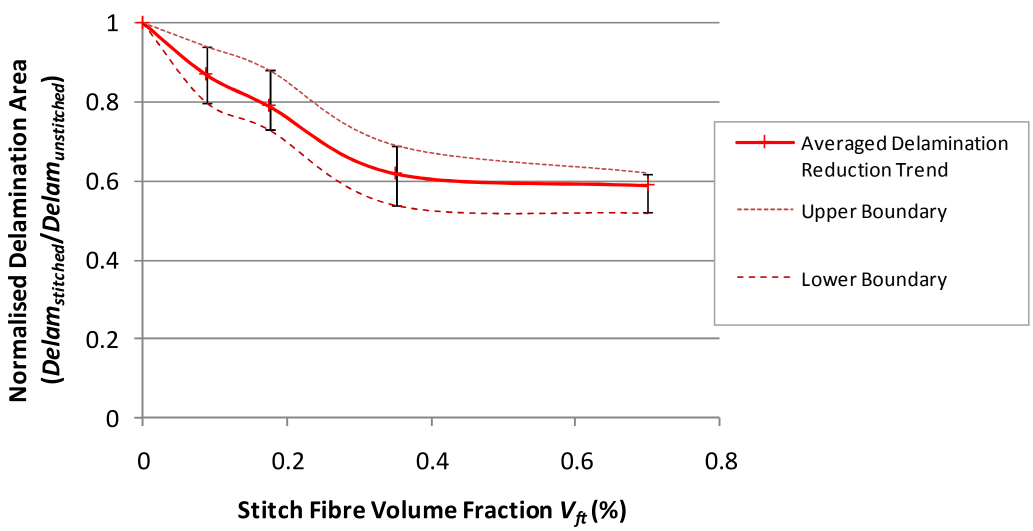

Figure 2. Impact-induced Delamination Reduction Trend for stitched composites [2].

In this paper, the DRT is validated by the use of Quasi-Static Indentation (QSI) test. QSI test is considered analogous to LVI test based on the slow dynamic response of the material behavior [3, 4]. Specimens, stitched with different stitch configurations, are supported in the same test fixture as in the LVI test. They are also quasi-statically loaded using the same impactor as in the LVI test. The specimens are loaded and unloaded at 0.5mm indentation incremental depth to observe damage mechanisms using non-destructive inspection techniques, namely ultrasonic c-scan, x-ray radiography and x-ray micro computed tomography, to elucidate damage phenomena. Findings from QSI tests aim to offer insightful understanding of damage propagation in stitched composites. Results in delamination growth are used to compare with that proposed in DRT. Some limitations in DRT are discussed.

2 Materials and testing methods

2.1 Test specimens

The specimens were made using T800SC-24K (Toray Industries) carbon fibre fabric of 20-ply $[+45/90/-45/0/0/+45/90/90/-45/0]_S$. The linear density of Vectran stitch threads used in this study is 200 or 400 denier, with a stitch space and pitch of 3mm x 3mm (densely stitched) or 6mm x 6mm (moderately stitched). Vectran is selected as the stitch fibre because, besides having comparable properties with Kevlar, it is more superior due to its very low propensity to absorb moisture and performs better in interlaminar strengthening of stitched composites [5]. The type of stitch used is the Modified Lock stitch. After the stitching process (if any), resin transfer moulding (RTM) technique, using resin XNR/H6813, was adopted to consolidate the composite. Specimens of 100mm width and 150mm length were then cut out from a mother plate using a diamond wheel cutter. The averaged plate thickness of the 20-ply specimen is 4.1mm. All specimens are physically examined for any poor-resin regions and ultrasonic C-scanned for any internal delamination to ensure that they are free from any manufacturing related defects.

2.2 Experimental testing

Quasi-static indentation (QSI) test was performed using Instron 8852 test machine (100kN load cell) with a displacement rate of 0.5mm/min. The semi-spherical indenter has a diameter of 15.9mm and the specimen was placed on a support frame similar to the one used in the low-velocity impact (LVI) test [6, 7]. After each indentation step of 0.5mm, the specimen was unloaded and observed for damages, by conducting ultrasonic inspections using a 5 MHz probe and X-ray inspections using ZnI_2 penetrant. The specimen was subjected to both x-ray radiography and x-ray micro-computed tomography examination to observe in-plane and cross-sectional damages respectively. More details on these non-destructive evaluation techniques can be referred to [8]. After damage inspection, the specimen was again subjected to indentation at higher loading at the next 0.5mm step. By repeating these steps, damage progression of stitched composite was investigated. The test was terminated once final failure was reached. This test was similarly repeated for all unstitched and stitched composites.

3 Results and discussion

3.1 Load-displacement curves

Typical load-displacement curve obtained from the quasi-static indentation test is presented in Figure 3. It is observed that damage progression can be categorized into three stages: *damage initiation*, *damage propagation* and *final failure*. *Damage initiation* is characterized by the first observable slope change in the load-displacement graph, which often occurs between 1.0mm to 1.5mm indentation displacement in this study. *Final failure* is identified by the maximum force in the load-displacement curve, which is accompanied by an abrupt load drop. It is revealed that final failure load increases with increasing stitch density, as stitches are effective in suppressing delamination growth and eventually raising ultimate strength [1]. However, results also showed that damage initiation load decreases with increasing stitch density. This means that stitched composites are more susceptible to damage initiation at lower loads and this is attributed to the presence of weak resin-rich region around stitch loops, acting as crack initiation sites [7].

It is further observed that during the *damage propagation* stage (after damage initiation and before final damage failure), load-displacement curve of densely stitched composite exhibits very smooth curve line, indicating that composite damage is gradual and delamination spread is progressive. However, in moderately stitched and unstitched composites, the curves exhibit some irregular curve pattern with small abrupt load drop, especially at higher displacement, implying sudden damage growth and delamination propagation. This is due to the fact that when stitches are closely spaced, stitches act as effective crack arrestors for delamination damage, thus preventing sudden delamination widespread.

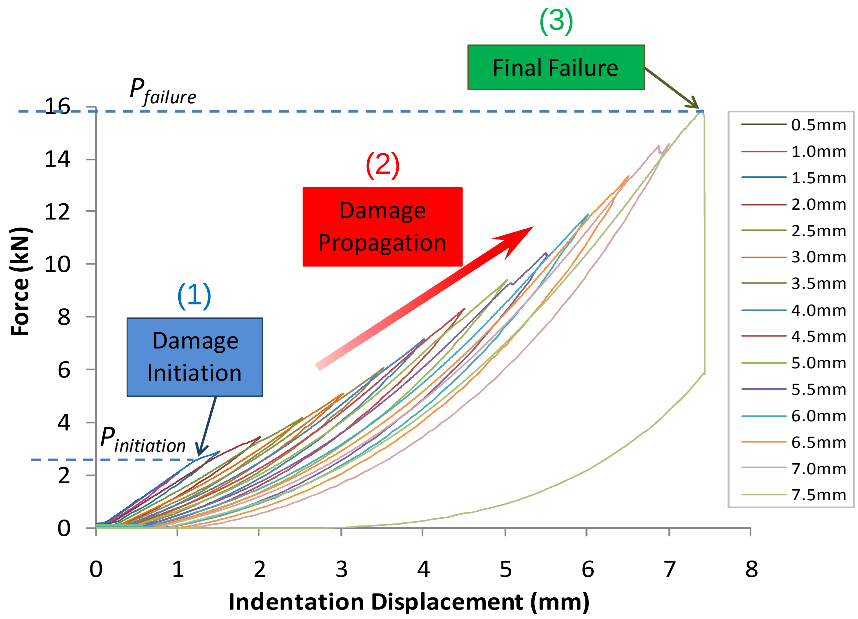

Figure 3. Typical load-displacement curve for quasi-static indentation test.

3.2 Delamination propagation

Typical ultrasonic c-scan images are shown in Figure 4. These images illustrate the evolution of damage in unstitched and stitched specimens with increasing indentation depth. The red and yellow regions at the center of the images represented the delamination damage area, while the blue region represented the undamaged area. It is obvious that delamination size increases with increasing indentation depth. At d=1.5mm, when damage first occurs, it is observed that unstitched specimen has much smaller damage than stitched composites. This means that stitched composites are more susceptible to impact damage initiation with lower damage initiation load. From Figure 4, we can recognize that the delamination growth in unstitched specimen is fast, reaching support frame boundary at d=5.0mm. The delamination growth of moderately stitched composite is equally fast, but to a smaller extend. In this case, the delamination shape is oblong, similarly observed in low-velocity impact tests [6]. This is attributed to the bending effect of thin laminate. For densely stitched composite, delamination growth is slow and well contained by the stitches. Damage does not reach specimen edge, but extent to support frame boundary at d=7.0mm.

The curves of delamination area against indentation depths for all specimens are plotted in Figure 5. It is clear that densely stitched configuration can suppress delamination growth effectively as indentation depth increases. Unstitched composite generally has the largest delamination area. Between 1.5mm<d<3.0mm, all curves seems to merge, indicating no effect of stitching when indentation depth is small. In fact, the effectiveness of stitching actually starts immediately after d=2.0mm, and gradually the effect of stitching becomes more prominent when indentation depth is large (d>4.0mm). It is evident that stitching suppresses delamination propagation, being remarkably effective in densely stitched composite. The stitching creates closing tractions acting across the crack, which shield the crack tip from the full effect of the crack opening stress. The driving force for propagation of delamination crack is greatly reduced and delamination growth is intensely suppressed. Moreover, delamination crack is effectively arrested by stitches in densely stitched specimens due to the presence of stitches in closer proximity. In authors' earlier work [8], it was revealed that crack arresting and crack bridging account for the main impact resistance mechanisms in stitched composites. It is worth noting that the interpretation of Figure 5 should be treated with care, especially when indentation depth is large. This is because boundary saturation occurs when delamination reaches the boundary edge, as seen in Figure 4, and the effect of boundary influence is not clearly reflected in the measured delamination area.

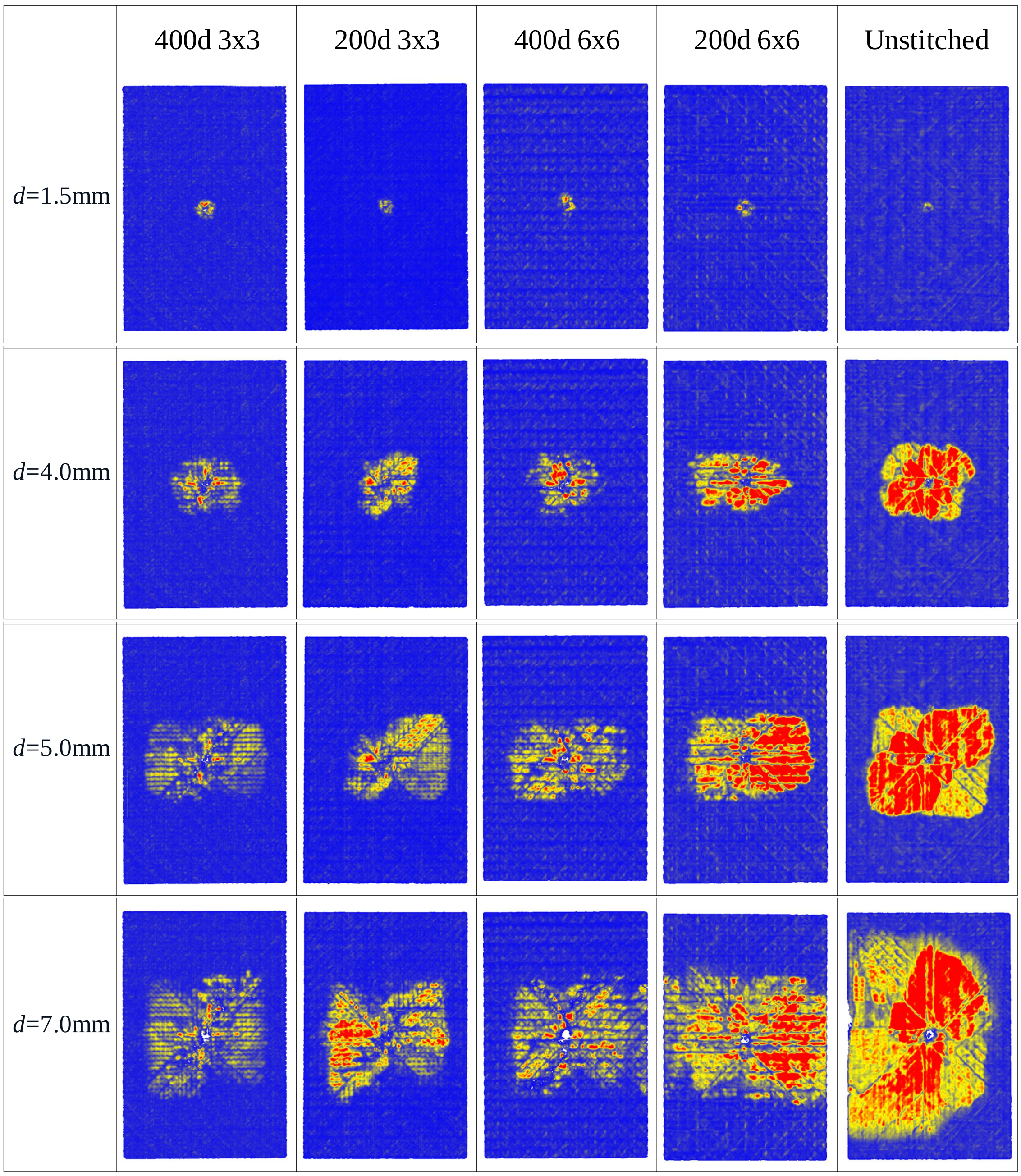

Figure 4. C-scan images showing delamination propagation during quasi-static indentation test.

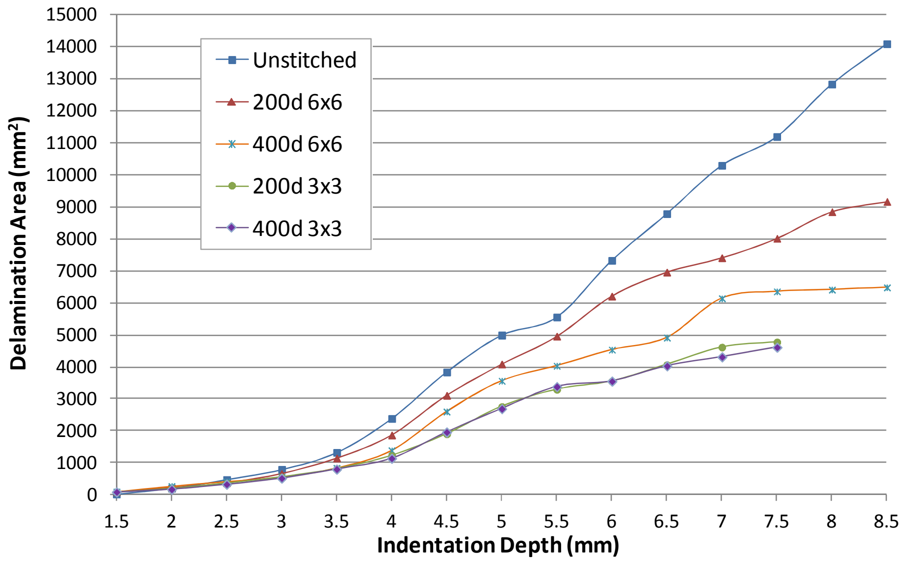

Figure 5. Delamination area against indentation depth.

3.3 Validation of DRT

Normalised delamination areas against indentation depth for the stitched specimens are displayed in Figure 6. It is obvious that when damage initiation first occur at *d*=1.5mm, the delamination area of stitched composite is larger than the unstitched counterpart. This is because stitch loops, being weak resin-rich regions, act as crack initiation sites, which subsequent create delamination growth. This indicates that DRT is not applicable when damage first started. As delamination starts to propagate, the influence of stitching becomes effective. It can be observed that for 200d 6x6 (V_{ft}=0.088%) and 400d 6x6 ((V_{ft}=0.175%) specimens, the normalized delamination area is around 80% and 70% respectively. In both cases, they fall along the lower boundary of DRT (Figure 2). The normalized delamination area for 200d 3x3 and 400d 3x3 specimens are very similar, almost merging to form the same trend. This is in line with the observation in DRT that delamination reduction is limited at around 60% when V_{ft} reaches around 0.4%.

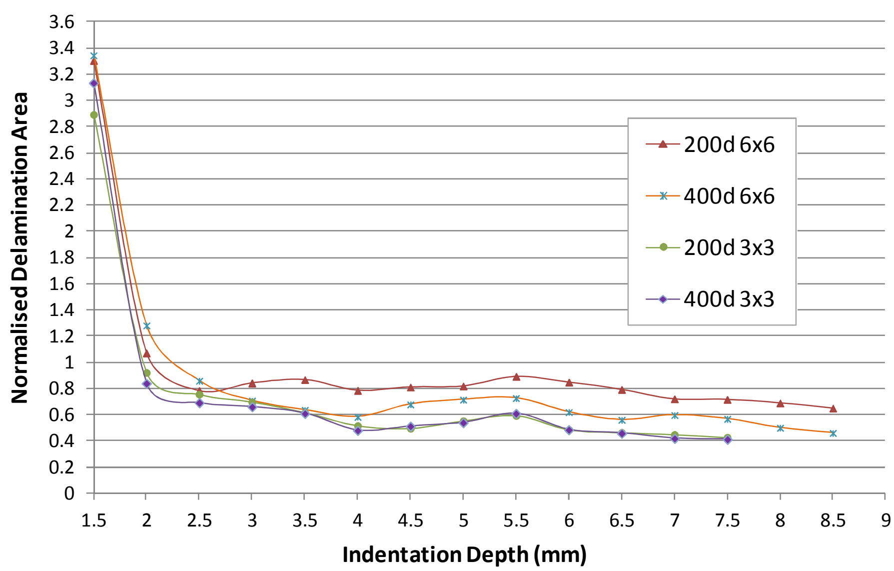

Figure 6. Normalised delamination area against indentation depth.

Fluctuations in the normalized delamination area seem to occur when d>5.5mm. Special caution must be noted at this stage, as the delamination area of the specimens, especially unstitched laminates, might have reached the boundary of the test fixture. In this case, the impact-induced delamination area is influenced by test boundary conditions and does not reflect the true delamination area under quasi-static indentation loading. As such, it would be better to ignore the normalized delamination area results when d>5.5mm.

4 Conclusion

In this study, quasi-static indentation (QSI) test is performed on stitched composites. Results reveal better understanding of damage progression in laminated composites due to the effect of stitching. The progressive delamination area measured during the QSI test is used to validate a recently proposed Delamination Reduction Trend (DRT). DRT is capable of predicting the effective reduction in impact-induced delamination area due to the influence of stitching. Results from QSI tests show good agreement with DRT. It is important to note that DRT is not applicable when damage initiation first started and that delamination growth must be sufficiently developed. However, adding to that, the delamination area should not have reached the boundary of the test fixture, affecting natural propagation.

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References

[1] Tan K.T., Watanabe N., Iwahori, Y., Ishikawa T. Effect of stitch density and stitch thread thickness on compression after impact strength and response of stitched composites. *Composites Science and Technology*, **72**, pp. 587-598 (2012).

[2] Tan K.T., Watanabe N., Iwahori, Y., Ishikawa T. Understanding effectiveness of stitching in suppression of impact damage: an empirical delamination reduction trend for stitched composites. *Composites Part A*, **43**, pp. 823-832 (2012).

[3] Aoki Y., Suemasu H., Ishikawa T. Damage propagation in CFRP laminates subjected to low velocity impact and static indentation. *Advanced Composite Materials*, **16**, pp. 45-61 (2007).

[4] Symons D.D. Characterisation of indentation damage in 0/90 lay-up T300/914 CFRP. *Composites Science and Technology*, **60**, pp. 397-401 (2000).

[5] Tan K.T., Watanabe N., Iwahori Y. Stitch fibre comparison for improvement of interlaminar fracture toughness in stitched composites. *Journal of Reinforced Plastics and Composites*, **30**, pp. 99-109 (2011).

[6] Tan K.T., Watanabe N., Iwahori Y. Effect of stitch density and stitch thread thickness on low-velocity impact damage of stitched composites. *Composites Part A*, **41**, pp. 1857-1868 (2010).

[7] Tan K.T., Watanabe N., Iwahori Y. Impact damage resistance, response and mechanisms of laminated composites reinforced by through-thickness stitching. *International Journal of Damage Mechanics*, **21**, pp. 51-80 (2012).

[8] Tan K.T., Watanabe N., Iwahori Y. X-ray radiography and micro computed tomography examination of damage characteristics in stitched composites subjected to impact loading. *Composites Part B*, **42**, pp. 874-884 (2011).